Cosmic ray recipes

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Abstract

Cosmic rays represent one of the most fascinating research themes in modern astronomy and physics. After almost a century since their discovery, a huge amount of scientific literature has been written on this topic and it is not always easy to extract from it the necessary information for somebody who approaches the subject for the first time. This has been the main motivation for preparing this article, which is a concise and self-contained review for whoever is interested in studying cosmic rays. The priority has been given here to well established facts, which are not at risk to get obsolete in a few years due to the fast progress of the research in this field. Also many data are presented, which are useful to characterize the doses of ionizing radiation delivered to organisms living on the Earth due to cosmic rays. The technical terms which are often encountered in the scientific literature are explained in a separate appendix.

1 Introduction

Cosmic rays (CR) represent a fascinating subject of research, which is recently witnessing a growing interest within the scientific community. With the next generation of cosmic ray detectors, like for example the Pierre Auger

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Observatory which is currently under construction, there is the hope that the questions posed by these cosmic particles will find soon some satisfactory answer. One should also note that the attention to CR is not only restricted to the traditional fields of high energy physics and astroparticles. This article is for instance the result of the authors' efforts to investigate the mutagenic effects of cosmic rays on cells. To this purpose, one needs to characterize very precisely the fluxes and intensities of particles arriving to the ground as an effect of the interaction of CR with the atmosphere of the Earth.

The increasing popularity of CR is accompanied by an increasing demand of information on this topic, but it is not always easy to extract this information from the huge amount of literature which has been written on CR during a period of almost a century after their discovery. An additional problem is that, looking at the scientific literature on CR, often concepts like the integral vertical intensity or the differential integrated flux are encountered. These terms sound somewhat puzzling and exotic for a reader that encounters them for the first time. These motivations have compelled us to prepare this short review, which would like to be a compact but self-contained reference on CR. The preference has been given here to well established facts, which are not in danger to become obsolete in a few years due to the fast progress in this topic. Moreover, a considerable effort has been done in order to explain in details and with the help of figures the technical terms used in the current scientific literature. The puzzles raised by the existence of ultra-high energy cosmic rays with energy of 10^{19}eV or higher, like the mystery of their origins or the apparent violation of the theory of relativity which is connected with them, have been just briefly mentioned. Hopefully, these puzzles will be solved with the next generation of cosmic rays detectors. Another aim of this work is to present data concerning the physical parameters, e. g. types of radiation, delivered effective doses and dose rates, fluxes and intensities of incoming particles, which characterize the radiation to which the organisms living on the Earth are exposed because of CR. These data are certainly of interest for scientists working in life sciences. Cosmic rays are in fact the source of an almost uniform background of ionizing radiation which is present everywhere on the Earth. Most of their energy arrives to the ground in the form of kinetic energy of muons. The latter particles are very penetrating and are able to travel for kilometers in water and for hundreds of meters in rock. Since ionizing radiation is mutagenic, it is very likely that the radiation of cosmic origin has shaped in some way the evolution of life on our planet, generating some kind of adaptive response in cells.

Finally, as already mentioned, this article is self-contained, but of course it is far from being complete, because it is impossible to cover all the immense literature which exists on cosmic rays. To integrate the material presented here, suggested further readings are for instance [1, 2, 3, 4, 5, 6] and references therein.

2 Cosmic rays and the natural background radiation

2.1 Introduction to cosmic rays

Cosmic rays, first discovered by Victor Hess in 1912, are charged particles accelerated at very high energies by astrophysical sources located anywhere beyond the atmosphere of the Earth. 89% of cosmic rays consists of protons, followed by $\alpha-$particles ($\sim 10\%$) and heavier nuclei ($\sim 1\%$) [1]. All elements of the periodic table, including transuranic elements, have been detected. More details on the composition of cosmic rays can be found in Ref. [2] and references therein.

Within the flux of incoming particles one can distinguish different components. The most relevant ones are galactic CR (GCR), solar energetic particles (SCR) and the anomalous CR (ACR) [8]. GCR originate from sources located in our galaxy outside the solar system. It is believed that GCR are a consequence of astrophysical events like stellar flares, stellar coronal mass ejections, supernova explosions, particle acceleration by pulsars [7]. Very often, the word cosmic rays refers only to GCR [1]. The smallest detectable energy of GCR is about 1 GeV. Below this energy, the screening effect of the solar wind is too strong to allow them to penetrate the heliosphere [9]. A detailed information on the interaction of GCR with the magnetic fields of the Sun and of the Earth is contained in Ref. [7] and references therein. Here we would just like to mention the action on CR of the galactic magnetic fields which are generated by the spinning of the Milky Way. These fields are relatively weak, because the average magnetic field in our galaxy is of

[1]These data are taken from Ref. [1]. Of course, as it always happens in the case of experimental data, there is some uncertainty due to measurement errors. For this reason, different authors report slightly different values as in the case of [7], which gives 95% for protons, 3.5% for α particles and 1.5% for all the rest. It should also be noted that the flux of particles below the energy of 10GeV strongly depends on the 11–year solar cycle.

the order of 10^{-10}T. However, since CR consist of charged particles traveling along huge distances, at the end these magnetic fields are able to bend their trajectories in a relevant way. At this point one should note that there are two different components in the magnetic fields of our galaxy, a regular one and a turbulent one, see Ref. [10]. The strengths and directions of the magnetic fields belonging to the turbulent component are random [9, 10]. Due to this randomness, the trajectories of CR are randomly bent. As a consequence, the flux of CR which arrives on the Earth is also random or, more precisely, isotropic. For this reason, it is not easy to ascertain where GCR are coming from. Besides being isotropic, the particle flux is constant in time too, so that GCR form an almost uniform background of ionizing radiation on the surface of the Earth. CR of energies up to 10^{21}eV have been observed. These are considerable energies for a microscopic particle. For example, the upper energy limit of 10^{21}eV corresponds in SI units approximately to 160 Joules. This is comparable to the kinetic energy of a ball of 0.8kg thrown at the speed of 50km/hour. The origin of such ultra high energy CR (UHECR) is so far unknown, but there are strong hints that they could be produced outside of our galaxy. Candidate sources of UHECR could be relativistic plasma jets from supermassive black holes [11], explosions of galactic nuclei [7], but other possibilities have been proposed, like magnetic monopoles, see for example [12]. The main evidence which suggests that UHECR are of extragalactic origin is provided by the fact that the magnetic fields which are present in the Milky Way are not able to trap CR of that energy. Indeed, already protons of energy higher than 10^{15}eV are able to escape the galactic confinement[2]. As a consequence, if protons of energies of 10^{19}eV or higher would be produced by sources located in our galaxy, they would escape it in all possible directions following trajectories which are almost straight lines. For this reason, the ultra high energy protons which reach the Earth should arrive along directions which are approximately parallel to the galactic plane. However, this conclusion is not confirmed by observations, see Refs. [13, 14] and references therein. Observations show in fact that the spatial distribution of ultra high energy protons is isotropic, so that their directions are not aligned with the galactic plane. This is of course a strong hint that UHECR are of extragalactic origin.

[2]In the case of heavier nuclei, the threshold energy for escaping the galactic confinement is higher than that of protons. It is for this reason that one observes a greater proportion of heavier nuclei with respect to protons in CR with energy above 10^{15}eV.

On the other side, there is at least one argument which seems to point out that the sources of UHECR are not very far from our galaxy. In fact, it has been noted that protons of energies above $5{\cdot}10^{19}$eV would lose their energy by interacting with the photons of the microwave (big bang) background. This effect was predicted in 1966, one year after the detection of the microwave background radiation, by Kenneth Greisen, Vadem Kuzmin and Georgi Zatsepin. The energy threshold of $5{\cdot}10^{19}$eV is called the GZK-limit, from the names of its discoverers. Protons with energies above that threshold will be slowed down during their travel to the Earth by the mechanism of energy-loss pointed out by Greisen, Kuzmin and Zatsepin until their energy falls below the GZK-limit. This mechanism is so efficient that, in practice, protons with energies higher than $5{\cdot}10^{19}$eV should not be observed on the Earth if their source is located at distances which are greater than 50Mpc [3]. Since ultra high energy protons have instead been detected, this implies that they originate from sources which are within the range of 50Mpc. Yet the known cosmic objects which could be able to accelerate protons to such high energies are at least at a distance of about 100 Mpc or more. So cosmic ray protons above this energy should not arrive on the Earth or we should explain why their formidable sources, which should be relatively near to us, remain invisible. These contradictions are known under the name of GZK paradox. On these points see Ref. [15].

Let's now discuss the remaining components of CR. Energetic solar events, like for instance solar flares, are able to accelerate particles up to some GeV very efficiently within the time of 10 seconds. The SCR are mainly protons, heavier nuclei and electrons. Finally, it is worth mentioning also the case of ACR. This kind of CR is mainly characterized by ions of elements which are difficult to ionize, including He, N, O, Ne and Ar. Moreover, ACR have a relatively low energy, up to a few hundreds of MeV [16]. It is thus improbable that CR of such a low energy could originate from the violent phenomena which produce GCR. Besides, we recall that CR of energy below 1GeV coming from outside the heliosphere cannot penetrate very deeply inside the solar system, because they are deflected by the solar magnetic fields. There are indeed evidences that ACR may be neutrally charged dust particles present in the interstellar gas near the border of the solar system

[3]Mpc stands for megaparsec. 50Mpc are approximately 150 millions of light years. This is about 1500 times the diameter of a galaxy and it is not a big distance in comparison with the cosmic scale of distances.

[1, 8, 17]. When these particles enter in contact with the far edges of the heliosphere, they are ionized by UV solar photons or by interactions with the particles within the solar wind. Once these dust particles have been ionized, they are accelerated by the shock waves formed when the solar wind encounters the interstellar plasma. Particles escaping the shocks may diffuse toward the inner heliosphere and arrive on the Earth as ACR. Actually, there are many open questions on the mechanism of ACR acceleration. Hopefully, these questions will be answered in 2007. By that date, in fact, the Voyager 1 should reach the region in which the shocks occur, which is thought to be somewhere between 75 and 100 AU from the Sun [4]. This will be the first time that an example of CR acceleration will be observed directly.

2.2 Interaction of CR with the Earth's atmosphere

When CR arrive near the Earth, they hit the nuclei of the atoms of the atmosphere, in particular nitrogen and oxygen, producing in this way secondary particles. The first interaction of the CR primary particle takes place in the top 10% of the atmosphere [21]. The most relevant reactions[5], remembering that 90% or more of CR consists of protons, are:

$$pp \longrightarrow pn\pi^+ \qquad \text{or} \qquad pp \longrightarrow pp\pi^0 \tag{1}$$

$$pn \longrightarrow pp\pi^- \qquad \text{or} \qquad pn \longrightarrow pn\pi^0 \qquad \text{or} \qquad pn \longrightarrow nn\pi^+ \tag{2}$$

$$\tag{3}$$

In the above reactions all the secondary particles are hadrons, namely protons p, neutrons n and pions in all their charged states $\pi^\pm, \pi^0$. Pions may in turn decay according to the following processes:

$$\pi^+ \longrightarrow \mu^+\nu_\mu \quad \text{and} \quad \pi^- \longrightarrow \mu^-\bar{\nu}_\mu \tag{4}$$

$$\pi^0 \longrightarrow \gamma\gamma \tag{5}$$

where the $\mu^\pm$'s are muons, the γ's are photons and $\nu_\mu, \bar{\nu}_\mu$ are respectively muonic neutrinos and their anti-particles. The mean life of pions is 26ns

[4] At the time in which this article was finished, a distance up to about 90 AU has been explored by Voyager 1. Some of the results of the observations can be found in Refs. [18, 19, 20].

[5] One should remember that the collisions of CR with the atmosphere gives raise also to less relevant reactions, which produce particles like kaons, η particles and even resonances.

for $\pi^{\pm}$ and 10^{-16} seconds in the case of π^0. For this reason, charged pions may still collide with air atoms before decaying, but it is very unlikely that this happens in the case of neutral pions, which have a very short average life. Other secondary particles, like protons, neutrons and photons interact very frequently with the atoms of the atmosphere giving raise in this way to a cascade of less and less energetic secondary particles. At the end, these particles are stopped by the atmosphere or, if the energy of the primary particle was sufficiently high, they can reach the ground.

The main mechanism of energy loss [6] of high energetic hadrons consists in the disintegration of the molecules of the atmosphere [22], see Fig 1. This leads to the creation of new particles through nuclear interactions like those shown in Eqs. (1) and (2). At lower energies, dissipative processes become predominant, in which the molecules of the atmosphere get either ionized or excited. The most relevant process of this kind in the case of heavy charged particles is the ionization of the molecules of the atmosphere. Lighter charged particles like electrons and positrons lose their energies not only by ionization, but also by bremsstrahlung. This consists in the radiative loss of energy of charged particles moving inside matter, when they are deflected by the electrostatic forces of the positive charged nuclei of the surrounding molecules. Photons and neutrons, the remaining relevant particles in the cascade, are examples of indirectly ionizing radiation. Their interaction mechanisms are more complicated than those of charged particles and will not be described here. The interested reader may find a more detailed account on the way in which radiation of different kinds interacts with matter in Ref. [23].

The total number of secondary particles N_{sec} within the cascade grows rapidly, mainly sustained by the processes of bremsstrahlung and pair production due to electrons, positrons and photons. Hadrons like protons and, to a less extent, neutrons, are easily stopped by the atmosphere, so that they increase relevantly the number of particles by disintegrating the molecules of air only during the first stages of the formation of the cascade. The decays of pions given in Eqs. (4) and (5) produce muons and photons of considerable energies. The muons are very penetrating particles and do not interact very much with the air. They lose a small fraction of their energy before reaching the ground by ionizing the molecules of the atmosphere. The photons give raise instead to electron-positron pairs e^+e^-. In turn, electrons and positrons create other electrons by ionization or other photons due to bremsstrahlung.

[6] Here and in the following energy means the kinetic energy of the particles.

In this way, while the cascade propagates inside the atmosphere, the number of its electrons, positrons and photons grows almost exponentially. The maximum number of particles inside the cascade is attained when the average energy per electron reaches the threshold E_T ~80MeV. When the energy of electrons in air falls below that threshold, ionization starts to prevail over bremsstrahlung as the main mechanism of energy loss of electrons in air and the process for increasing the number of particles described above ceases to be effective.

If the energy of the primary particle is below 10^{14}eV, essentially only the penetrating muons and neutrinos are able to arrive to the sea level, while the other particles in the cascade are absorbed at higher altitudes. Actually, neutrinos interact so rarely with matter that they could pass through a light year of water without undergoing any interaction. Thus, if one is concerned with the dose of ionizing radiation delivered by CR to the population, the contribution of neutrinos can simply be neglected. Muons are more dangerous for the health. They have a short mean life at rest (2.2ns), but since they travel at very high speeds, they manage to reach the surface of the Earth due to the relativistic dilatation of time. Part of these muons can still decay, giving raise to electrons e^- or positrons e^+, mainly according to the process: $\mu^\pm = e^\pm + \nu_e + \nu_\mu$.

When the energy of the primary particles is instead above 10^{14}eV, the cascade of secondary particles arrives to the ground before being stopped by the atmosphere. In that case, the cascade is called with the name of air shower, see Fig.1. To be precise, the effects of an air shower started by a primary particle of 10^{14}eV are relevant up to altitudes comparable to that of Mount Everest [24, 25]. Only air showers generated by primaries of energy of about 10^{15}eV or higher are able to reach also the typical altitudes of inhabited areas and arrive to the sea level. The frequency of these air showers is relatively high, because the total flux of primary particles with energy $E \geq 10^{15}$eV is of about 100 particles per m^2 per year. Giant air showers produced by primaries of energies beyond 10^{20}eV are much more rare: their total flux is of 1 particle per km^2 per century [1]. More data concerning fluxes of incoming primary particles and an explanation of how these data are measured using ground detectors, can be found in Refs. [6, 26].

In the air shower we distinguish a nucleonic component, a muon component and an electromagnetic component. The nucleonic component is generated by high energetic protons and neutrons, which disintegrate the atoms of the air giving raise to other protons and neutrons. The fluxes of electrons,

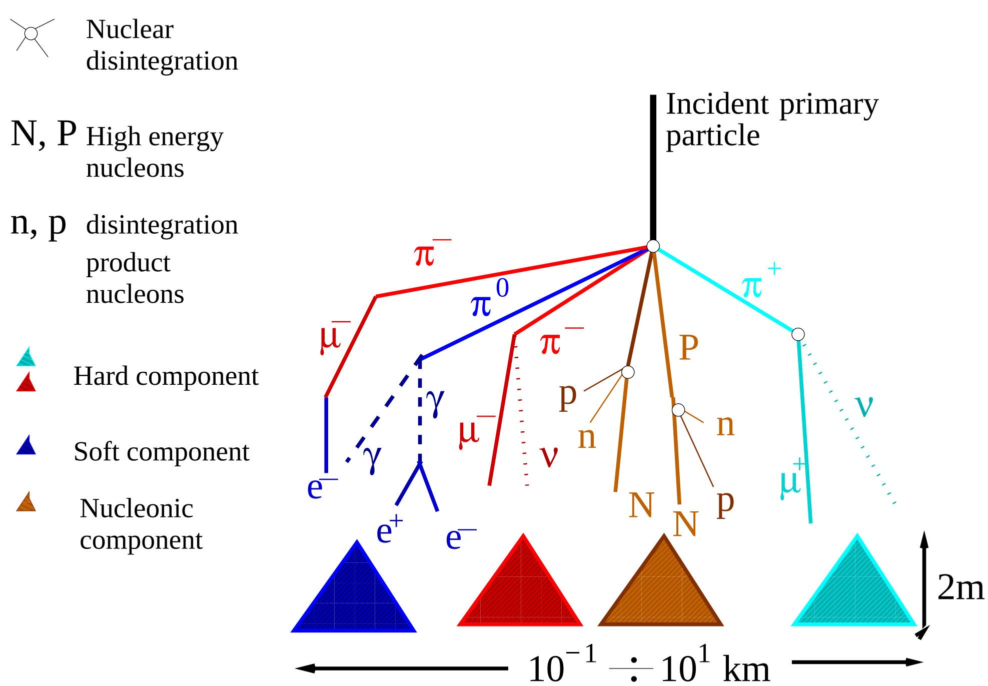

Figure 1: This figure illustrates schematically how air showers generate from cosmic rays. The high energetic primary particle, usually a proton, whose trajectory has been denoted in black, starts to interact with the molecules of the upper atmosphere. In this way, secondary particles are produced, which give raise to other particles (tertiary, quaternary etc.) via other interactions with the atmosphere or via decay processes. The total flux of particles can be divided in a *electromagnetic component* (photons, electrons and anti-electrons or positrons), see the blue trajectories in the figure, in a *muon component*, see the cyan and red trajectories, and finally in a *nucleonic component* (mainly protons, neutrons, rarely pions) denoted in brown. At the sea level, the air shower has the form of a pancake, whose height is around two meters, while its radius usually around a few hundreds of meters, but may reach some tents of kilometers in the case of very energetic cosmic rays. The nucleonic component is usually confined in a narrow cone centered along the direction of the incoming primary particle.

positrons and photons started by the decay of the π^0's, together with the electrons and positrons coming from the decay of muons or from the ionization due to the hadrons, form the electromagnetic component. In the early times of CR research, electrons and positrons have been called the soft component, while muons coming from the decay of the charged pions have been called the hard component. These names originate from the fact that muons are very penetrating and thus they may be regarded as "hard" particles. For instance, at the energy of 1 GeV, the range[7] of muons is $2.45{\cdot}10^5$g cm^{-2}. This implies that in water, which has a density of 1 g cm^{-3} at 4 C, muons run along an average distance of 2.45 km before being stopped completely. In standard rock, which has a density of 2.65 g cm^{-3} [2], this average distance reduces to about 900 meters.

At the sea level, the air shower has approximately the form of a pancake with an height of 1-2 meters. Its extension in the other two directions, defined as the distance in which 90% of the total energy of the shower is contained, is given by the so-called Molière radius. For example, in the case of an air shower started by a primary particle of an energy of 10^{19}eV (10 EeV) the Molière radius has a length of about 70 meters. The real extension of the shower is much bigger and some of the muons may be detected up to a distance of a few kilometers from the core [26]. Usually the nucleonic component, which is composed by heavier particles than those of the muon and electromagnetic components, is less deflected from the direction of the incident primary particle by the interactions with the atmosphere and it is thus concentrated in a narrow cone inside the air shower. The center of the cone is roughly aligned with the direction of the original primary particle. The number of secondary particles which arrives on the ground with an air shower is huge. Considering particles whose energies are greater that 200keV, an air shower generated by a 10EeV primary particle contains up to 10^{10} particles, mostly photons, electrons and positrons. Electrons outnumber positrons in the ratio 6 to 1. The maximum number of particles, i. e. the so-called point of shower maximum or simply shower maximum, is attained at an altitude of 2–3 km above the sea level. Many other data and diagrams describing the propagation of air showers in the atmosphere may be found in Ref. [27].

[7] The range is defined as the average depth of penetration of a charged particle into a material before it loses all its kinetic energy and stops. The concept of range has a meaning only in the case of charged particles whose energy is kinetic energy which is lost continuously along their paths due to ionization and bremsstrahlung processes [23].

When air showers approach the ground, about 85% of their energy is concentrated in the electromagnetic component. The contribution of the muon and nucleonic components is thus much less relevant. The situation changes completely if we consider all CR, and not only those which have sufficient energy to give raise to an air shower. As we see in Fig. 2, muons are in fact responsible for about 85% of the total equivalent dose delivered by CR to the population at the sea level. As a consequence, globally it is the muon component the most significant from the energetic point of view and not the electromagnetic component. The reason of this fact is that primary particles with energy $E \geq 10^{15}$, namely those which can produce air showers, form just a minimal fraction of the total amount of CR arriving on the Earth. For example, the total flux of particles with energy $E \geq 10^{12}$eV (1 TeV), is of 1 particle per m^2 per second, i. e. a factor of $3{\cdot}10^5$ higher than the total flux of CR with energy $E \geq 10^{15}$ reported above. In other words, there is an overwhelming number of CR with energy lower than 10^{15}eV which are not able to start an air shower, but may still generate energetic muons. Being very penetrating particles, these muons are not stopped easily by the atmosphere and reach the sea level altitude, where they represent the biggest source of ionizing radiation of cosmic origin. Other particles which deliver relevant doses of ionizing radiation to the population on the surface of the Earth are photons, electrons and neutrons. The percent contributions to the total equivalent dose of the various components of CR as a function of the altitude is given in Fig. 2. In that figure, which has been published in 1996, the curve concerning neutrons should be taken with some care, because the data on neutron fluxes in the atmosphere were still sparse at that time [14]. Other data about energies and fluxes of particles due to CR will be given in the next Section. We note that protons and neutrons prevail at higher altitudes, but they are rapidly absorbed by the atmosphere and muons become dominant at lower altitudes.

2.3 Intensities and fluxes of CR

CR are the source of an avalanche of secondary particles which hit constantly the surface of the Earth. To determine the energy and number of these particles, their directions of arrival and their distribution in time, quantities like the integral vertical intensity or the differential directional intensity are measured. The meaning of these quantities is explained in details in a separate Appendix at the end of this article. In this section, we present some

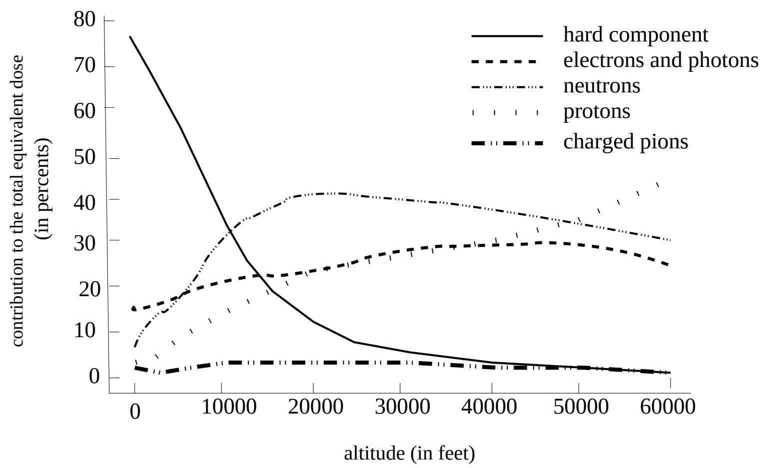

Figure 2: Percent contribution of the various CR components to the total equivalent dose at different altitudes. This figure is based on data of Ref. [7].

experimental data which are useful in order to characterize the contribution of the muon, electromagnetic and nucleonic components to the background of ionizing radiations on the ground due to CR.

The integral vertical intensity (IVI in the Appendix, see Eq. (27)) of the muon component with energy above 1 GeV at sea level is approximately $I^{hard}_{ivi}(\theta = 0) \sim 0.70 \cdot 10^{-2}$ cm^{-2}s^{-1}sr^{-1}[2]. The integral directional intensity of muons in the other directions, which are at an angle θ with respect to the vertical direction, has the following behavior: $I^{hard}_{idi}(\theta) \propto I^{hard}_{ivi}(\theta = 0) \cos^2\theta$. More complete phenomenological formulas for the angular distribution of CR intensities may be found in Refs. [2, 28, 29]. As Fig. 3 shows, muons arriving to the ground are very energetic. The most frequent muon energy is 500MeV, while the average muon energy is 4GeV. There is almost no protection from this source of radiation, since, as we have seen before, high energetic muons are able to penetrate thick layers of concrete and rocks.

The integral vertical intensity for electrons plus positrons with energies greater than 10, 100 and 1000 MeV is very approximately given by[2]:

$$I^{el+pos}_{ivi}(\theta = 0, E_{min} > 10MeV) \sim 0.30 \cdot 10^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \quad (6)$$
$$I^{el+pos}_{ivi}(\theta = 0, E_{min} > 100MeV) \sim 0.06 \cdot 10^{-2}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \quad (7)$$
$$I^{el+pos}_{ivi}(\theta = 0, E_{min} > 1000MeV) \sim 0.02 \cdot 10^{-3}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \quad (8)$$

Moreover, the total flux of electrons plus positrons amounts approximately to

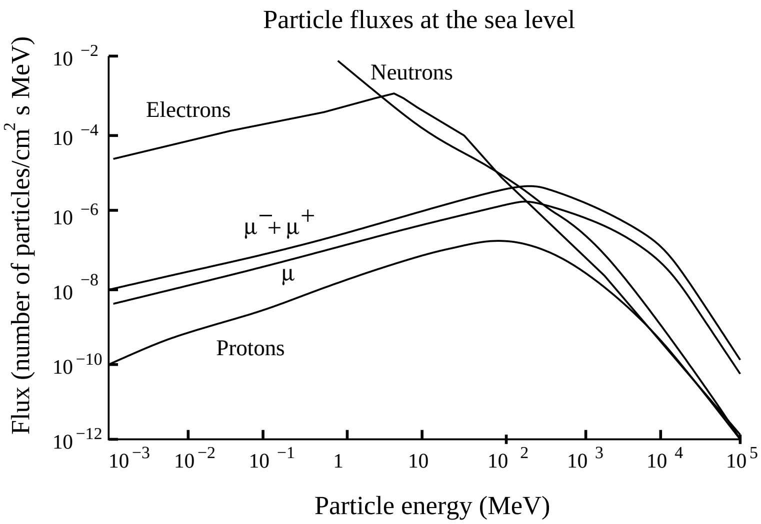

Figure 3: Differential integrated flux (see Eq. (37) of the Appendix) of the different components of CR related radiation at the sea level. This figure has been created on the basis of an analogous figure appeared in Ref. [30]. The original data are taken from Ref. [32].

30% of the total particle flux which is reaching the ground due to cosmic rays. Always according to [2], the ratios of photons to electrons + positrons is approximately 1.3 above 1 GeV and 1.7 below the critical energy $E_T \sim 80$MeV mentioned above. The differential flux on the ground of the various components of radiation related to CR can be seen in Fig. 3. One may observe that different particles become predominant at different energies. In the lowest portion of the energy range, electrons are predominant. At energies of around 1 MeV electrons are taken over by fast neutrons which arise mainly due to the de-excitation of atmospheric nuclei following compound-nucleus reactions [31] [8]. Electrons become once again predominant in the energy range going from a few MeV up to some tens of MeV. Starting from energies

[8] Roughly speaking, in a compound nucleus reaction a neutron or a proton, but also an $\alpha-$particle interacting with the nucleus of an atom creates a nucleus of higher atomic number which is metastable and decays after a short period of time. For example, a possible compound-nucleus reaction is: $p + {}^{63}Cu \longrightarrow {}^{64}Zn^*$. The de-excitation of the metastable nucleus produces others neutrons and protons, e. g.: ${}^{64}Zn^* \longrightarrow {}^{63}Zn + n$ or ${}^{64}Zn^* \longrightarrow {}^{62}Cu + n + p$. Compound-nucleus reactions become possible only if the energies of the incoming nucleons or alpha particles are such that the de Broglie wave lengths of these particles are comparable with the size of the hit nucleus.

approximately above 200MeV, the number of muons becomes overwhelmingly high in comparison to that of the other particles. In considering the above data, one should of course take into account the fact that, at low energies, let's say below 10MeV, particle fluxes are strongly dependent on many factors, including weather conditions, so that there are big uncertainties in their measurement up to an order of magnitude [32]. Moreover, all the data presented so far in this Section refer to the sea level altitude. With increasing altitudes, the contribution to the particle flux given by protons and neutrons, the nucleonic component of CR, becomes more and more relevant (see Fig. 2) and is predominant above atmospheric depths of approximately 500 g cm^{-2} [9].

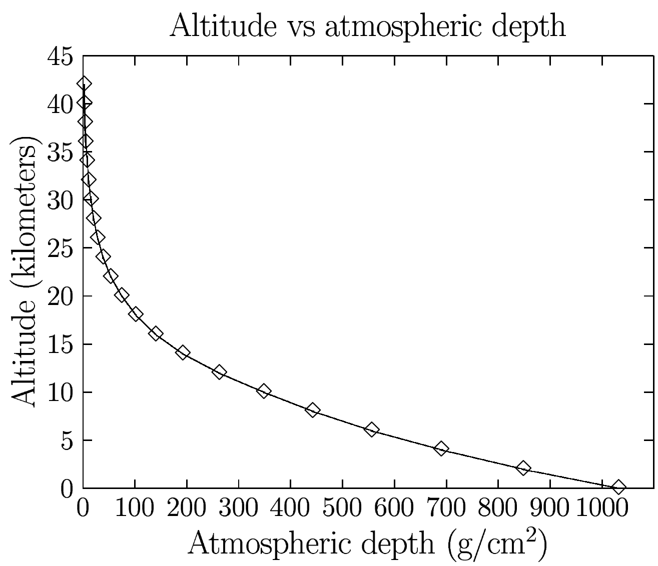

Figure 4: Conversion diagram from atmospheric depth to altitude. The data corresponding to the dots are taken from Ref. [33].

To conclude this Section, we provide also some data regarding the particle flux outside the heliosphere. The total flux of CR in the galaxy is large, about 100000 particles m^{-2}s^{-1} [34]. Much lower is for example the integral directional flux of CR primaries with $E > 2 \cdot 10^{15}$eV is about $\Phi_{idf} = 75000$

[9] The atmospheric depth is a quantity which is often used to measure the altitude. For convenience, we give in Fig. 4 a diagram which is useful to make the conversion from atmospheric depth in g/cm^2 to altitude in kilometers.

particles km^{-2}sr^{-1}day^{-1}. This datum has been derived using a formula for the integral directional flux given in Ref. [25], which is based on the results of measurements and simulations of incoming cosmic ray fluxes reported in Ref. [35]. The dependence of this flux on the direction of the incoming particles is minimal since, as mentioned before, the distribution of these particles is isotropic due to the presence of random magnetic fields in the Milky Way. Finally, the integral directional flux of particles with energies above 10^{20}eV is $\Phi_{idf} = 1$ particle km^{-2} sr^{-1} century^{-1} [36]. With such a small flux, the investigation of CR with energy beyond the GZK limit requires detectors which cover a very large area. Perhaps with the next generation of detectors it will be possible to solve the puzzles connected with UHECR.

2.4 Dose of ionizing radiation from CR in present times

In present times[10] the effective dose rate (EDR) delivered by CR to the human population varies from a minimum of 300μSv year^{-1} to a maximum of 2000μSv year^{-1}. This wide range depends on many factors, the most important one being the altitude. At sea level, the value which usually is given for the EDR is 270 μSv year^{-1}, or equivalently 31 nSv h^{-1}. One should keep in mind however that this estimation is the result of population-weighing average. As a matter of fact, even if the altitude is fixed at the sea level, the EDR still changes with the latitude within a range of variation of approximately 10%. Strictly speaking, 270 μSv year^{-1} is the dose rate received by the population living at a latitude which is near the 30° parallel. It turns out in fact from the distribution of the population on the Earth that this is the average latitude at which people are living. Besides, the above value of EDR takes into account only the contributions of muons and of the electromagnetic component. The nucleonic component, which at the sea level is essentially consisting of neutrons, gives to the average EDR at the sea level an additional contribution of 48 μSv year^{-1} or, equivalently, 5.5 nSv h^{-1}. The figures concerning neutrons should be taken with some care, since up to the time in which Ref. [14] was released, the available data on neutron fluxes were sparse. If one considers also the different altitudes in which the population lives, the population-weighted EDR is of 380 μSv year^{-1}, corresponding to an average habitant of the planet Earth living approximately near the 30°

[10]The data concerning the present levels of radiation coming from CR are taken from the United Nations Report of the year 2000 [14].

parallel and at an altitude of 900 meters above the sea level.

3 Conclusions

In this review a short but thorough account has been provided on what it is known about cosmic rays, starting from their origin in space and arriving to the doses of ionizing radiation delivered by them to the human population. Only the sources of CR have not been discussed here, because this argument is outside the aims of this article. Much attention has been dedicated to fluxes and intensities of CR and of the particles arriving on the ground as an effect of the cascades initiated by CR in the atmosphere. These quantities are of interest for scientists working in different subjects. Apart from research in high energy physics and astronomy, the fluxes and intensities of particles of cosmic origin are also studied for radioprotection purposes [7, 14] and for their capability of causing potentially harmful failures in computers and electronic storage devices [34]. Fluxes of CR are also carefully measured due to their relevance to space explorations, see for example [37]. Finally, in Appendix A the various kinds of fluxes and intensities of CR and related particles which one encounters in research articles about CR have been defined and their meaning has been illustrated. Concrete expressions for these quantities have been given in terms of mass densities, velocity distributions and energy densities. Both relativistic and non-relativistic cases have been treated. Up to now, a systematic classification and explanation of these quantities such as that provided in this work was missing in the scientific literature on CR. The necessity of filling this gap justifies the length of this Appendix.

A Appendix A: Definitions of intensity, flux and related quantities

We have seen that, in order to characterize the intensity and flux of charged particles which arrive on the Earth due to CR there exist an entire zoo of observables. Their names and meanings may sound puzzling for somebody who is not acquainted with them. Moreover, the same observable is sometimes called with different names by different authors, or, on the contrary, the same name is used to describe two slightly different observables in different contexts. Besides, it is not easy to find an explanation of these observables

in the scientific literature. Books on radiative transport contain often useful information, see for example [38], however these books describe the intensity and flux of radiation emitted by an energy source. Here we are instead dealing with intensity and flux of particles arriving at a detector. For these reasons and also to make this article self-contained, in the following it will be made an effort to explain the meaning of the various quantities which are relevant in the physics of CR.

A.1 Differential directional intensity

The differential directional intensity (DDI) I_{ddi} is defined [11] in such a way that the quantity

$$dN_i = I_{ddi} dS d\Omega dE_i dt \tag{9}$$

represents the number of particles of a given kind incident upon the infinitesimal element of area dS during the time dt within the element of solid angle $d\Omega$ perpendicular to dS and within the energy interval $[E_i, E_i+dE_i]$. Here the index $i = 1, 2, 3, \ldots$ labels the different kinds of particles (electrons, protons, muons etc.)

To compute explicitly the I_{ddi} in terms of physical parameters like particle velocity and mass or energy density, let us consider a point P in the space, whose position with respect to a cartesian system of coordinates $Oxyz$ is given by the radius vector $\mathbf{r} = (x, y, z)$. In the following, it will be convenient to define a second reference system with origin in P and spherical coordinates ϖ, θ, ϕ, with $0 \leq \theta \leq \pi$ and $0 \leq \phi \leq 2\pi$, see Fig. 5. We introduce also the infinitesimal vector element of surface $d\mathbf{S} = dS\mathbf{n}$. The area and the orientation of $d\mathbf{S}$ are given by dS and by the unit vector $\mathbf{n}$ which is normal to dS respectively. The element of surface dS is centered around the point P. Now we wish to count the number of particles of a certain type, e. g. electrons, which hit per unit of time the surface dS and whose velocities $\mathbf{v}_i$ are oriented according to a certain direction, given for instance by the unit vector $\mathbf{e}_R(\theta, \phi)$. In mathematical terms this last condition is expressed as follows: $\mathbf{v}_i = |\mathbf{v}_i|\mathbf{e}_R(\theta, \phi)$. We will see that, in the case of the flux, the direction of $\mathbf{e}_R(\theta, \phi)$ may be arbitrary. However, in the case of the intensity, the element of surface $d\mathbf{S}$ should be by definition perpendicular to the vector

[11] Here we follow Ref. [39], in which a very clear and precise definition of the related concept of directional intensity is presented

$\mathbf{e}_R(\theta, \phi)$. In other words:

$$\mathbf{n} = \mathbf{e}_R(\theta, \phi) \tag{10}$$

If the particles are non-relativistic, one may express the DDI in terms of the velocity and mass density of particles:

$$\mathbf{v}_i = |\mathbf{v}_i(E_i)|\mathbf{e}_R(\theta, \phi) \tag{11}$$

$$\rho_i = \rho_i(\mathbf{r}, \theta, \phi, E_i, t) \tag{12}$$

The norm of $\mathbf{v}_i$ is a function of the energy of the particle given by the well known relation:

$$E_i = \frac{m_i}{2}|\mathbf{v}_i|^2 \tag{13}$$

Let us note that the distribution of density of mass ρ_i, which can also be a sum of Dirac delta functions, depends on the angles θ, ϕ, on the position $\mathbf{r}$ of the point P in the space, on the energy E_i and on the time. There is however no dependence on the radial coordinate ϖ. We will see below why it is not necessary to add the radial coordinate in the list of the arguments of ρ_i. Looking at Fig. 5, it is clear that the number of particles incident upon the surface dS from the specified direction is given by:

$$dN_{i,\mathbf{e}_R}(\mathbf{r}, \theta, \phi, E_i, t) = \frac{\rho_i}{m_i}|\mathbf{v}_i|d\mathbf{S} \cdot \mathbf{e}_R(\theta, \phi)dt \tag{14}$$

In order to derive Eq. (14) it has been used the fact that the total mass dM of the particles which traverse the surface dS in the interval of time dt is $dM = \rho_i|\mathbf{v}_i|d\mathbf{S}\cdot\mathbf{e}_R dt$. The number of such particles is obtained after dividing the total mass dM by the mass m_i of a single particle of type i. The dependence of $dN_{i,\mathbf{e}_R}(\mathbf{r}, \theta, \phi, E_i, t)$ on the kinetic energy E_i becomes explicit after eliminating the norm of the velocity $|\mathbf{v}_i|$ from the right hand side of Eq. (14) using Eq. (13). Finally, the scalar product $d\mathbf{S} \cdot \mathbf{e}_R(\theta, \phi)$ gives the effective area which is hit by the particles incoming from the direction $\mathbf{e}_R(\theta, \phi)$. Since by definition of DDI the particle velocities are always perpendicular to dS, i. e. parallel to $d\mathbf{S}$, see Eq. (10), we have that

$$dN_{i,\mathbf{e}_R}(\mathbf{r}, \theta, \phi, E_i, t) = \frac{\rho_i}{m_i}|\mathbf{v}_i|dSdt = \frac{\rho_i}{m_i}\sqrt{\frac{2E_i}{m_i}}dSdt \tag{15}$$

Now we are in a position to understand why it is not needed to take into account the dependence on ϖ of mass density. The reason is that just a small

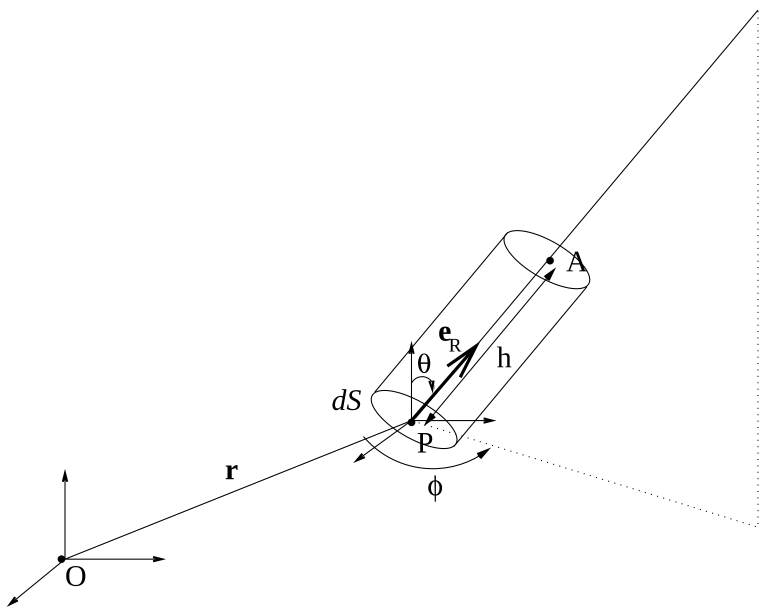

Figure 5: This figure shows the geometrical setup for the definition of the differential directional intensity. The normal vector $\mathbf{n}$ to the infinitesimal surface dS at the point P coincides with the vector $\mathbf{e}_R$ which gives the direction of the incoming particles. The particles that will be traversing the surface dS within the interval of time dt are those contained in the volume $h \cdot dS$, where $h = |\mathbf{v}_i| dt$.

portion of space near the point P is considered, so that the radial coordinate is varying within the interval $[0, h]$, where $h = |\mathbf{v}_i| dt$. Clearly, the variation of ρ_i with respect to the radial coordinate is negligible within this infinitesimal interval.

Let us remark that, in real measurements, the number of particles coming from a particular direction is usually very small, so that it is better to consider an entire set of directions, for instance those characterized by slightly different angles θ', ϕ' included within the range

$$\theta \leq \theta' \leq \theta + \Delta\theta \tag{16}$$

$$\phi \leq \phi' \leq \phi + \Delta\phi \tag{17}$$

where $\Delta\theta$ and $\Delta\phi$ denote finite quantities and not infinitesimal ones. Clearly, the unit vectors $\mathbf{e}_R(\theta', \phi')$ associated to these directions span a surface of area:

$$A = \int_{\theta}^{\theta+\Delta\theta} d\theta' \sin(\theta') \int_{\phi}^{\phi+\Delta\phi} d\phi' \tag{18}$$

on a sphere of unit radius, see Fig. 6. Always for experimental reasons, it

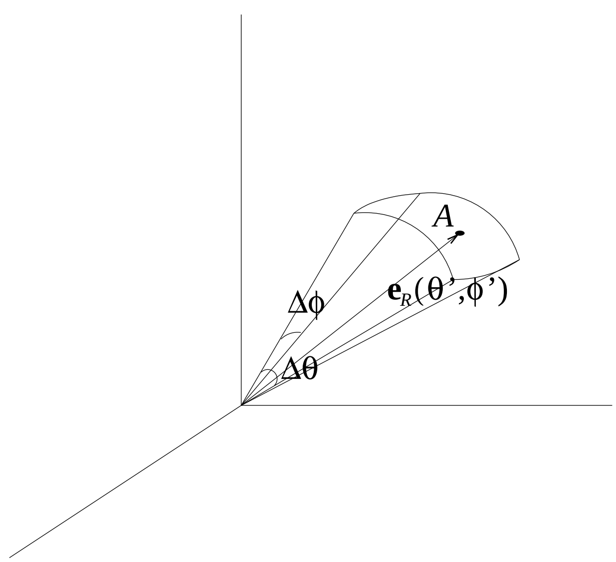

Figure 6: Area A spanned on a sphere of unit radius by the unit vectors $\mathbf{e}_R(\theta', \phi')$. The values of θ' and ϕ' are defined in Eqs. (16) and (17).

will also be convenient to enlarge the set of possible particle energies to a

finite interval:

$$E_i \leq E_i' \leq E_i + \Delta E_i \tag{19}$$

Now we count the incoming particles in the neighborhood of the point P according to the following procedure. For each value of the energy E_i' within the interval (19) and for each of the directions falling within the range of angles of Eqs. (16–17), we count the number of particles traversing a surface of fixed area dS and perpendicular to that direction in the sense of Eq. (10). Successively, summing over all the numbers obtained in this way, we get the final result $dN_{i,\Delta\theta,\Delta\phi,\Delta E_i}(\mathbf{r},\theta,\phi,E_i,t)dSdt$. In terms of mathematical equations, this means that the quantity $dN_{i,\Delta\theta,\Delta\phi,\Delta E_i}(\mathbf{r},\theta,\phi,E_i,t)$ is computed by integrating the infinitesimal number of particles $dN_{i,\mathbf{e}_R}(\mathbf{r},\theta,\phi,E_i,t)$ of Eq. (14) as follows:

$$dN_{i,\Delta\theta,\Delta\phi,\Delta E_i}(\mathbf{r},\theta,\phi,E_i,t) = \int_{E_i}^{E_i+\Delta E_i} \int_{\theta}^{\theta+\Delta\theta} \int_{\phi}^{\phi+\Delta\phi} \frac{\rho_i}{(m_i)^{\frac{3}{2}}} \sqrt{2E_i} d\Omega' dSdt \tag{20}$$

To write the above equation we have used Eq. (13) in order to express the speed $|\mathbf{v}_i|$ as a function of the kinetic energy E_i and the fact that the infinitesimal element of solid angle $d\Omega'$ is given by:

$$d\Omega' = \sin(\theta')d\theta' d\phi' \tag{21}$$

The quantity $dN_{i,\Delta\theta,\Delta\phi,\Delta E_i}(\mathbf{r},\theta,\phi,E_i,t)$ describes the intensity of particles with energy in the interval (19) which arrive at the point P from all the directions spanning the area A of Eq. (18) on a sphere of unit radius.

To compute the DDI, it is now sufficient to take the limit in which $\Delta\theta$ and $\Delta\phi$ become infinitesimally small. In that case:

$$dN_{i,\Delta\theta,\Delta\phi,\Delta E_i}(\mathbf{r},\theta,\phi,E_i,t) \sim dN_i(\mathbf{r},\theta,\phi,E_i,t) \tag{22}$$

with

$$dN_i(\mathbf{r},\theta,\phi,E_i,t) = \frac{\rho_i}{(m_i)^{\frac{3}{2}}} \sqrt{2E_i} d\Omega dE_i dSdt \tag{23}$$

It is easy to realize that the number of particles $dN_i(\mathbf{r},\theta,\phi,E_i,t)$ of Eq. (23) coincides with the number of particles entering in the definition of DDI of Eq. (9). Comparing these two equations, we find that

$$I_{ddi}(\mathbf{r},\theta,\phi,E_i,t) = \frac{\rho_i}{(m_i)^{\frac{3}{2}}} \sqrt{2E_i} \tag{24}$$

Eq. (24) provides a nice relation between the DDI and the mass density ρ_i. From Eq. (24) it turns out that the units in which the DDI is measured are $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}$, where sr is a shorthand for steradiant, the unit of solid angles. In SI units one should replace centimeters by meters and GeV's by Joules.

As a final remark, let us note that the DDI carries a lot of information about the intensity of particles incoming from different directions. We will also see that the DDI is related to the energy density of particles. On the other side, the DDI is an observable which is mainly related to the point in which it is measured. In particular, it is not possible to integrate the quantity I_{ddi} in dS in order to extend its meaning to an arbitrary finite surface S. The reason is that, in the definition of the DDI the vector element of surface $d\mathbf{S}$ is constrained to satisfy Eq. (10). Of course, in a real measurement the infinitesimal element of surface dS is necessarily approximated by a finite surface ΔS, which may be for example the sensor of some particle detector. However, if one wishes to measure the number of particles traversing an arbitrary finite surface S, one should introduce the concept of flux. This will be done in Subsection A.3.

A.1.1 Quantities related to the differential directional intensity

Starting from the differential directional intensity I_{ddi} it is possible to construct several other quantities which are often encountered in the literature.

Integral directional intensity: The integral directional intensity (IDI) I_{idi} is obtained by integrating the DDI over some finite interval of energy $\Delta E_i = E_{i,max} - E_{i,min}$:

$$I_{idi}(\mathbf{r}, \theta, \phi, E_{i,min}, E_{i,max}, t) = \int_{E_{i,min}}^{E_{i,max}} I_{ddi}(\mathbf{r}, \theta, \phi, E_i, t) dE_i \tag{25}$$

where, of course, $E_{i,min} \geq 0$ in the non-relativistic case. Moreover, $E_{i,max} \in [0, \infty]$. The units of I_{idi} are $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$.

Differential vertical intensity: In many experiments it is measured the intensity of particles arriving on the surface of the Earth from the vertical direction, i. e. the direction that from the ground points

toward the center of the earth [12]. For this reason, the DDI in the vertical direction, which is supposed here to coincide with the value of the angle $\theta = 0$ of our spherical system of coordinates, has deserved a separate name and it is called the differential vertical intensity (DVI) I_{dvi}. The I_{dvi} is defined as follows:

$$I_{dvi}(\mathbf{r}, E_i, t) = I_{ddi}(\mathbf{r}, \theta = 0, \phi, E_i, t) \tag{26}$$

The units of DVI are the same of the units of the DDI.

Integral vertical intensity The integral vertical intensity (IVI) gives the number of particles coming from the vertical direction with respect to our coordinate system ϖ, θ, ϕ and with energies comprised within the interval $[E_{i,min}, E_{i,max}]$ which traverse a unit surface in the unit of time:

$$I_{ivi}(\mathbf{r}, t) = \int_{E_{i,min}}^{E_{i,max}} I_{ddi}(\mathbf{r}, \theta = 0, \phi, E_i, t) dE_i \tag{27}$$

Integrated intensity: The integrated intensity (II)[13] I_{ii} is defined as the integral of the DDI over all possible directions and energy values[39]:

$$I_{ii}(\mathbf{r}, t) = \int_0^{+\infty} dE_i \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta I_{ddi}(\mathbf{r}, \theta, \phi, E_i, t) \tag{28}$$

The integrated intensity is measured in units $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Of course, if one integrates the DDI only over all possible directions the result is a quantity which may be called the differential integrated intensity.

A.2 Energy density of particles and the intensity in the relativistic case

The specific directional density (SDD) $u_{sdd}(\mathbf{r}, \theta, \phi, E_i, t)$ is defined here as the kinetic energy of particles of type i per unit of volume, of energy and of solid angle. Sometimes the SDD is also called differential directional density. The quantity:

$$dU = u_{sdd}(\mathbf{r}, \theta, \phi, E_i, t) dV d\Omega dE_i \tag{29}$$

[12] Sometimes one considers the intensity of particles in the near vertical direction, where the values of the angle θ between the trajectories of the particles and the gravity force spans over a finite interval, such as for instance $0.9 \leq \sin\theta \leq 1$.

[13] Strictly speaking the name integrated integral intensity would be more correct.

represents the total kinetic energy carried by particles which are inside an element of volume dV and have velocities $\mathbf{v}_i$ whose directions span a small element of solid angle $d\Omega$ centered around the direction of the unit vector $\mathbf{e}_R(\theta, \phi)$. The norms of these velocities are determined by the condition that the energy of the particles must be within the infinitesimal interval $[E_i, E_i + dE_i]$. Clearly, the number of particles dN with the above characteristics which are inside the small volume dV at the time t is given by the total energy of the particles divided by the energy of each single particle:

$$dN = u_{sdd}(\mathbf{r}, \theta, \phi, E_i, t) dV d\Omega \frac{dE_i}{E_i} \tag{30}$$

In the non-relativistic case we have seen that the relation between the kinetic energy E_i and the norm of the velocity $|\mathbf{v}_i|$ is provided by Eq. (13). In the relativistic case, this equation must be substituted with the following one:

$$|\mathbf{v}_i| = \frac{c}{E_i + m_i c^2} \sqrt{E_i^2 + 2 m_i c^2 E_i} \tag{31}$$

The relativistic and non-relativistic expressions of the energy density u_{sdd} may be found in Ref.[40].

At this point, we wish to derive the DDI for particles which attain relativistic speeds in terms of the energy density. We note to this purpose that the particles which will traverse the surface dS in the time dt while arriving from the direction perpendicular to dS, are contained in the infinitesimal volume:

$$dV = |\mathbf{v}_i| dS dt \tag{32}$$

As a consequence, the number of particles dN_i of Eq. (9) may be expressed in terms of the SDD as follows:

$$dN_i = u_{sdd}(\mathbf{r}, \theta, \phi, E_i, t) |\mathbf{v}_i| dS dt d\Omega \frac{dE_i}{E_i} \tag{33}$$

Comparing Eq. (9) with Eq. (33), we obtain a relation between the DDI and the SDD:

$$I_{ddi} = u_{sdd}(\mathbf{r}, \theta, \phi, E_i, t) \frac{c}{E_i^2 + m_i c^2 E_i} \sqrt{E_i^2 + 2 m_i c^2 E_i} \tag{34}$$

where we have used Eq. (31) in order to write the speed $|\mathbf{v}_i|$ as a function of the energy E_i. Eq. (34) is the analogous of Eq. (24) in the relativistic case with the mass density ρ_i replaced by the energy density.

At this point, the derivation of the related quantities of the DDI, like for instance the integral directional intensity or the differential vertical intensity, proceeds as in the non-relativistic case of Subsection A.1.

Finally, following an analogous calculation of the total energy density of electromagnetic radiation presented in Ref. [38], it is possible to compute the total kinetic energy density $u_{ted}(\mathbf{r}, t)$ of the particles per unit of volume:

$$u_{ted}(\mathbf{r}, t) = \int_{m_i^2 c^4}^{+\infty} dE_i \int d\Omega \frac{E_i^2 + m_i c^2 E_i}{c\sqrt{E_i^2 + 2m_i c^2 E_i}} I_{ddi}(\mathbf{r}, \theta, \phi, E_i, t) \tag{35}$$

A.3 Differential directional flux and related quantities

The definition of the differential directional flux (DDF) Φ_{ddf} is very similar to that of the DDI. The difference is that, in the case of the DDF, the direction of the normal $\mathbf{n}$ to the element of surface $d\mathbf{S}$ does not need to coincide with the direction of the velocity of the incoming particles $\mathbf{e}_R(\theta, \phi)$. More precisely, the DDF is defined in such a way that the quantity

$$dN_{i,\mathbf{e}_R}^f = \Phi_{ddf} dS dt dE_i d\Omega \tag{36}$$

represents the number of particles of a given kind traversing the infinitesimal surface element dS during the time dt within the element of solid angle $d\Omega$ and within the energy interval $[E_i, E_i + dE_i]$. The superscript f has been added to remember that now a flux is being computed and not an intensity.

To compute the DDF, let us imagine that we wish to measure it in a neighborhood of a point P. Since such measurements are usually performed on the ground, to fix the ideas we assume that the point P is very near (a few meters or less) to the surface of the Earth. The particle detector is approximated as a small and flat surface, which is centered around P. One side of the surface, that in which there are the sensors and which is thus able to detect the fluxes of incoming particles, is always directed toward the sky, while the opposite side is pointing toward the ground, see Fig. 7. To express this all in mathematical terms, we introduce an infinitesimal element of surface dS and we choose a system of coordinates x_P, y_P, z_P at the point P in such a way that dS lies in the horizontal plane $z_P = 0$. In polar coordinates ϖ, θ, ϕ this means that the direction of the unit vector $\mathbf{n}$ which is normal to dS is given by the angle $\theta = 0$. Furthermore, the orientation of $\mathbf{n}$ is such that it points downward, i. e. toward the ground. Since we are measuring

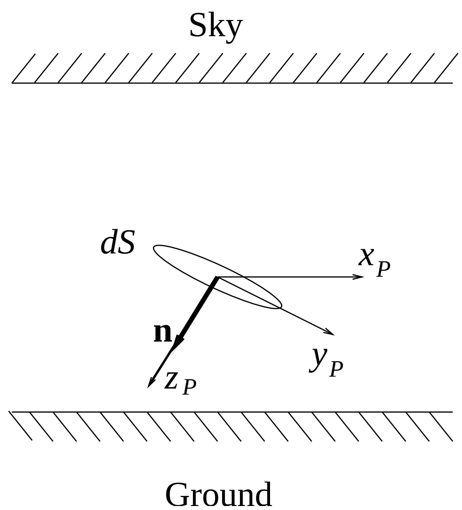

Figure 7: This figure shows the schematic experimental setup used to measure the flux of particles of cosmic origin on the ground. The detector is represented as an infinitesimal element of surface dS. The active part of the detector is on the upper side of the surface, which points toward the sky.

only particles which traverse the upper side of the surface dS in a downward sense, this implies that:

$$\mathbf{n} \cdot \mathbf{e}_R(\theta, \phi) = \cos\theta \geq 0 \tag{37}$$

i. e. the normal vector $\mathbf{n}$ and the particle velocity $|\mathbf{v}_i|\mathbf{e}_R(\theta, \phi)$ form an angle θ, see Fig. 8. Clearly, Eq. (37) is satisfied only in the interval $0 \leq \theta \leq \pi 2$ The volume of particles dV which will traverse dS coming from the direction $\mathbf{e}_r(\theta, \phi)$ is shown in Fig. 8 and it is given by: $dV = |\mathbf{v}_i| dt \cos\theta$. The number of those particle in the non-relativistic case is thus given by

$$dN^f_{i,\mathbf{e}_R} = \frac{\rho_i |\mathbf{v}_i|}{m_i} dS dt \cos\theta \tag{38}$$

This is the analog of Eq. (14) in the case of the flux. The factor $\cos\theta$ results after evaluating the scalar product $\mathbf{n} \cdot \mathbf{e}_R(\theta, \phi)$ using Eq. (37). As in the case of the intensity, in real measurements it is better to consider particles coming from different directions and carrying different energies, instead of fixing the attention to a particular direction and a particular energy. However we should remember that, in the computation of the DDF, the orientation of

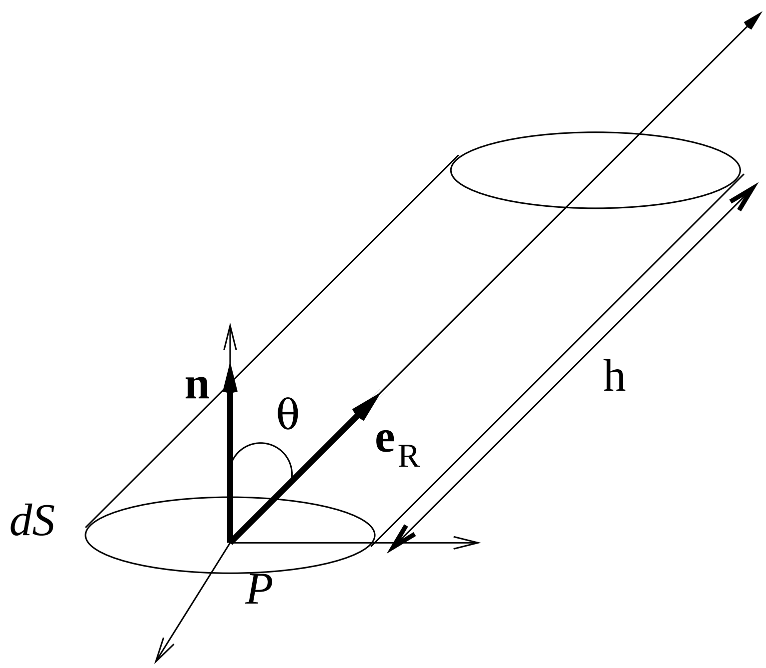

Figure 8: This figure shows the geometrical setup for the definition of the differential directional flux. The normal vector $\mathbf{n}$ to the infinitesimal surface dS at the point P makes an angle θ with the vector $\mathbf{e}_R$ which gives the direction of the incoming particles. The particles of type i with velocity $|\mathbf{v}_i|\mathbf{e}_R(\theta, \phi)$ which will traverse the surface dS within the interval of time dt are those contained in the volume $h \cdot dS \cos\theta$, where $h = |\mathbf{v}_i|dt$.

the surface $d\mathbf{S}$ remains fixed, what is changing is the direction of the incoming particles. At this point the procedure to obtain the differential directional flux is entirely similar to that used in deriving the explicit expression for the DDI of Eq. (24). The final result for the DDF is :

$$\Phi_{ddf}(\mathbf{r}, \theta, \phi, E_i, t) = \frac{\rho_i}{(m_i)^{\frac{3}{2}}} \sqrt{2E_i} \cos\theta \tag{39}$$

The units of the DDF are the same as the units of the DDI.

A.3.1 Observables related to the DDF

In analogy with what has been done in the case of the intensities, one may construct other observables starting from the DDF. For example, after integrating the DDF with respect to the energy one obtains the **integral directional flux** (IDF), while the **differential vertical flux** (DVF) corresponds to the value of the DDF in the case $\theta = 0$. Clearly, the DVF coincides with the DVI. The **differential integrated flux** $\Phi(\mathbf{r}, E_i, t)$, which can be found in standard textbooks, is defined in such a way that the quantity $dN^f_{i,int} = \Phi(\mathbf{r}, E_i, t) dS dt$ coincides with the number of particles of a given kind and of given energy E_i traversing in a downward sense [14] the element of surface dS:

$$\Phi(\mathbf{r}, E_i, t) = \int_0^{\frac{\pi}{2}} d\theta \int_0^{2\pi} d\phi \Phi_{ddf}(\mathbf{r}, \theta, \phi, E_i, t) \sin\theta \tag{40}$$

The subscript *int* in $dN^f_{i,int}$ means integrated and it is referred to the fact that, to derive $\Phi(\mathbf{r}, E_i, t) dS dt$, one needs an integration over $d\Omega$. This flux can be measured in units $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$. Starting from the expression of $\Phi(\mathbf{r}, E_i, t)$ it is possible to compute the integral integrated flux, often called **total flux**:

$$\Phi(\mathbf{r}, t) = \int_{E_{i,min}}^{E_{i,max}} \phi(\mathbf{r}, E_i, t) dE_i \tag{41}$$

The concept of flux is usually connected with vector fields. In the present case, the vector field is provided by the so-called differential directional intensity field

$$\mathbf{I}_{ddi} = I_{ddi} \mathbf{e}_R \tag{42}$$

[14]We recall that downward means here that the angle between the normal vector $\mathbf{n}$ and the vector $\mathbf{e}_R$ which determines the direction of the particle velocity must be within the range $[0, \frac{\pi}{2}]$.

where $\mathbf{e}_R$ is the unit vector which defines the direction of the velocity of particles. In terms of the DDI field, the flux may be expressed as follows:

$$\Phi(\mathbf{r}, E_i, t) = \int d\Omega \mathbf{I}_{ddi} \cdot \mathbf{n} \tag{43}$$

according to the usual definition of flux.

Contrarily to the DDI, the DDF may also be integrated with respect to the element of area dS. As we have anticipated before, this fact allows to define the flux of particles traversing an extended surface S. To compute the flux of particles in the case of an extended surface S, it will be convenient to parametrize this surface with the help of two parameters σ_1 and σ_2, so that a point of S in the space will be denoted by the triplet of cartesian coordinates $x(\sigma_1, \sigma_2)$, $y(\sigma_1, \sigma_2)$ and $z(\sigma_1, \sigma_2)$ or, shortly, by the radius vector $\mathbf{r}(\sigma_1, \sigma_2)$. For each point P of the surface, corresponding to a given value of the parameters σ_1 and σ_2, we have seen that it is possible to compute the differential flux of particles $\Phi(\mathbf{r}(\sigma_1, \sigma_2), E_i, t)$ traversing a small element dS of S. The total flux $\Phi_S(E_i, t)$ of particles of energy E_i incoming upon S within the interval of time dt is obtained by integrating $\Phi(\mathbf{r}(\sigma_1, \sigma_2), E_i, t)$ with respect to dS, where dS will now depend on σ_1 and σ_2:

$$\Phi_S(E_i, t) = \int_S \Phi(\mathbf{r}(\sigma_1, \sigma_2), E_i, t) dS(\sigma_1, \sigma_2) \tag{44}$$

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